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Final Report

p-Mode Scattering by Sunspots and Subsurface Magnetic Fields

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Summary of Research

1. Observations of p-Mode Scattering in Solar Active Regions:

During the course of this research project we have studied the acoustic scattering properties of several large sunspots and plage as determined from a Fourier-Hankel decomposition of p-mode amplitudes as measured from long duration sets of observations made at the South Pole in 1988 and 1990 and most recently with GONG data. In Braun (1995b) we report some of these measurements of p-mode absorption and scattering phase shifts as functions of the incident mode properties (degree, radial order and azimuthal order). The principal results are summarized below.

In sunspots we observed a distinct modulation of the absorption with temporal frequency in a fashion which is very nearly independent of the degree of the mode. In particular, the absorption exhibits a broad peak at 3 mHz, an absence of absorption at 5 mHz, and a rise in absorption at higher temporal frequencies. This variation is in good qualitative agreement with a prediction of a model of p-mode absorption by slow mode conversion described first discussed by Spruit and Bogdan (1992 ApJ 391, L109) and developed further by Cally and Bogdan (1993 ApJ 402, 721). Control tests made by repeating the analysis in a region of quiet Sun have confirmed a recent observation by Bogdan, et al. (1993 ApJ 406, 722) that the quiet Sun shows an apparent acoustic emission. In particular. we found a significant anticorrelation between the absorption coefficient in the quiet Sun and the values measured in a nearby sunspot.

The scattering phase shifts increase with the degree of the modes and the increase is faster than a linear relation. At constant degree the phase shifts increase with temporal frequency (radial order) before leveling off at a roughly constant value. We suggest that this behavior is consistent with a relatively shallow sound speed perturbation produced by the spots. The variation of the phase shift and the absorption with azimuthal order suggest the phase shifts are largely produced within the area of the sunspot, while significant absorption is occurring in a more extended region. Related to this observation is the finding that isolated plage. while absorbing p-modes, do not produce measurable phase shifts.

A significant goal of the proposed work involved identifying a signature, either p-mode absorption or scattering, of completely submerged magnetic field. One line of research involves performing the scattering measurements at the location of emerging sunspots prior to their appearance at the solar surface. Braun (1995a) presented a study of one such emerging region observed in the 1988 South Pole dataset. We found that substantial p-mode scattering is apparently occurring 36 to 48 hours prior to the spot emergence. During this time, the outward propagating p-modes are shifted backwards in phase from the inward traveling modes. This negative phase-shift decreases in magnitude reaching zero at the time of sunspot emergence. At later times, the phase-shift becomes positive, consistent with measurements made in evolved sunspots.

Recently it was suggested that the relatively small lifetimes of high degree p-modes might cause an apparent decrease in p-mode absorption from sunspots, if the waves are analyzed within an annulus which is comparable or larger than the coherence length of the modes (Bogdan, et al. 1993 ApJ. 406, 588). We have demonstrated conclusively that this effect is real and measurable. This was done by repeating the sunspot/p-mode absorption measurements for a range of annulus sizes in the 1988 South Pole data. The modes with the highest wavenumbers (and temporal frequencies) show a clear decrease in absorption as the mean radius of the annulus is increased (Bogdan and Braun 1995).

2. Modeling of Scattering Phase-shifts:

In a collaboration between the PI and Y. Fan (NSO) and D.-Y. Chou (Tsing Hua Univ., Taiwan), we modeled the scattering of p-mode waves in a polytropic atmosphere by localized inhomogeneities in wave speed, pressure and density of the medium (Fan. Braun, and Chou 1995). The effect of the inhomogeneities is attributed to a source term in the pressure wave equation. This inhomogeneous wave equation for the scattered waves is solved under the simplification of the Born approximation. From the solution for the scattered waves, we compute the phase shifts between the incoming and outgoing waves of individual modes.

We found that the variations of the computed phase shifts with degree l and radial order n of the modes show different behavior for inhomogeneities with different characteristic depths. Depths significantly shallower than the depth of the modes seem to show a phase shift dependence on l and n that is similar to the qualitative behavior of the observed phase shifts produced by sunspots. Direct quantitative comparison of the computed phase shifts with observations are limited to modes with lower degree ($l \leq 200$) where the observed phase shifts are reasonably small so that the Born approximation is applicable. We found that for inhomogeneities with a sound speed contrast reasonable for sunspots. occupying a volume described by a characteristic depth $D \approx 10^8$ cm, and horizontal radius $R \approx 2.5 \times 10^9$ cm, the computed phase shifts at lower l range are in agreement with the observed phase shifts from sunspots in both their magnitudes as well as their variation with l and frequency (or n).

We have formulated and constructed a numerical program for calculating the acoustic scattering by magnetic inhomogeneities. taking into account the Lorentz force from the magnetic field which causes anisotropy of the medium. Our calculations of scattering using a self-similar Shülter-Temesvary sunspot flux tube model in a truncated polytropic atmosphere show that the results are very sensitive to the specification of the upper boundary conditions of the medium and the magnetic flux tubes. The contribution to the p-mode scattering phase shift is sharply weighted towards the surface layer (with a depth ~ 1000 km) of the convection zone where the plasma β changes sharply from $\gg 1$ to less than 1, i.e. the structure of the magnetic flux tube changes from gas pressure dominated to magnetically dominated. In addition, we find that the inclination of magnetic field lines in the surface layer also plays an important role in determining the results of scattering. Only when the direction of wave propagation is nearly perpendicular to the field lines does the wave experience an increased phase speed of propagation and hence produces a phase shift that is consistent in sign with the observed results. The direction of wave propagation becomes nearly vertical in the surface layer. This means that the flaring of the magnetic flux tube field lines into horizontal directions in the surface layer of the convection zone may be essential to account for the observed p-mode phase shifts.

3. Diagnostics of Subsurface Flows From Sunspots:

In addition to "refractive" perturbations sunspot flux tubes produce in acoustic waves as a result of the additional restoring Lorentz force and the changes of thermodynamic conditions within them, the presence of a subsurface flow field surrounding the sunspot flux tubes can cause Doppler frequency shifts of propagating acoustic waves.

In collaboration with C. Lindsey at SPRC and others at the National Solar Observatory, we have used alternately spatially and spectrally sensitive methods employing high degree p-modes to detect extended subsurface horizontal flows associated around sunspots. The first of these methods employs "acoustic power maps", which have been filtered in the

Fourier domain to show Doppler signals caused by horizontal flows (Lindsey, et al. 1996). These maps, constructed from K-line images obtained at the South Pole in 1991, appear to show the presence of outflows from active regions which, for mature regions seem to be predominately concentrated at depths greater than 8 Mm below the surface. p-modes.

In the second analysis, we decomposed p-mode waves in an annular region surrounding a sunspot into incoming and outgoing cylindrical waves and detected a relative frequency shifts between the in and out components in the same South Pole data (Braun et al. 1996). These frequency shifts suggest subsurface radial outflows consistent with the analysis performed by Lindsey, et al. Similar analysis of three sunspots with data obtained from the GONG network in 1995, however, failed to show significant frequency shifts. It is thereby plausible that some other unknown mechanism may be responsible for the signatures seen in the South Pole data.

4. Holography:

In collaboration with C. Lindsey we have developed the basic principles of "helioseismic holography", an analytic technique intended for diagnostics of subsurface structure. It is based on the computational application of spatially resolved observations to the surface of an acoustic model of the solar interior. The observed surface oscillations are applied to the model in time reverse, and the model is then computationally sampled at various desired depths in its interior. We have explored computational approaches from two different perspectives, the "spectral" and the "spatial" Diagnostics for subsurface sources and sinks as well as refractive and Doppler effects are derived (Lindsey and Braun, 1996).

Publications:

Braun, D. C. 1995a "Sunspot Seismology: New Observations and Prospects" in GONG 1994: Helio- and Astero-Seismology from the Earth and Space, ASP Conf. Series, ed.: Ulrich, T., Rhodes, E. & Däppen, W., (PASP:San Francisco), 250.

Braun, D. C. 1995b "Scattering of p-Modes by Sunspots. I. Observations" ApJ, 451, 859.

Fan, Y., Braun, D. C. and Chou, D. 1995 "Scattering of p-Modes by Sunspots. II. Calculations of Phase Shifts from a Phenomenological Model" ApJ, 451, 877.

Bogdan, T. J. and Braun, D. C. 1995 "Active Region Seismology", in: Proc. 4th SOHO Workshop: Helioseismology, ESA SP-376, eds: Domingo, V. et al., (ESTEC: Noordwijk), 376, 31.

Lindsey, C., Braun, D. C., Jefferies, S. M., Woodard, M. J., Fan, Y., Gu, Y., and Redfield. S. 1996 "Doppler Acoustic Diagnostics of Subsurface Solar Magnetic Structure" ApJ. 470, 636.

Lindsey, C., and Braun, D. C., 1996 "Helioseismic Holography" ApJ, submitted.

Braun, D. C., Fan, Y., Lindsey, C. and Jefferies, S. M., 1996 "Diagnostics of a Subsurface Radial Outflow From a Sunspot" ApJ, submitted.

Inventions and Subcontracts:

No inventions or subcontracts have been made in the performance of this work.